Wave Induced Mine Burial and Sediment Transport in Coastal Environment: Wave and Sediment Transport Modeling Studies

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LONG-TERM GOALS

The long-term goal of this work is to develop numerical simulation techniques for predicting wave-induced sediment transport and bed evolution in the coastal zone (order 10 meter depth outside the surf zone), at horizontal scales of tens of meters or less, and the scouring/burial around objects/obstacles (mine-like), partially buried in the bottom. This research was initially motivated by the Navy's need to improve mine countermeasures (MBP), in support of joint littoral warfare, for which a key paradigm was to locate a clear or low mine- and obstacle-density path. More generally the laboratory validated modeling tools developed in this work will help improve both our fundamental understanding of, and ability to predict physical processes governing wave-current-induced morphodynamic changes, in coastal and estuarine environments of active sediment transport (e.g., ripple migration).

OBJECTIVE

In the past year, our objective was to extend the capabilities, integration, numerical efficiency and ultimately predictive abilities of two coupled numerical models simulating wave-(current)-induced flows and sediment transport over the seabed and around partially buried obstacles. These models were: (i) a two-dimensional (2D) fully nonlinear and inviscid Numerical Wave Tank (2D-NWT; initially developed at the University of Rhode Island; URI; Grilli and Subramanya, 1996; Grilli and Horrillo, 1997), and (ii) a three-dimensional (3D) fully viscous Navier-Stokes, Large Eddy Simulation model, with imbedded sediment transport model (3D-NS-LES; initially developed at Stanford University, and coupled in collaboration with Prof. Street and co-workers; Zedler and Street, 2001). In an earlier phase of this work, these models had been coupled and tested for a single idealized application, thus providing a proof of concept (Gilbert, 2005; Gilbert et al. 2005, 2007). The latter work clearly demonstrated the relevance of our modeling approach to simulate wave-induced flows and sediment transport around partially buried circular objects (mines) near the surfzone. Many aspects of the modeling, however, were initially oversimplified or idealized (i.e., flat bottom, quasi-2D object geometry, no moving bed algorithm, simple periodic incident waves) or arbitrary (sediment pick-up algorithm), and needed to be extended or refined for such computations to become both predictive and useful in solving scientific and practical problems of interest to this Navy program. For solving meaningful practical problems, the models also needed to be streamlined and optimized, and implemented and run on a massively parallel supercomputer cluster.

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APPROACH

In an earlier phase of this work, as part of collaborative work with Stanford University, the 2D-NWT developed at URI, based on Fully Nonlinear Potential Flow (FNPF) equations solved by a Boundary Element Method (BEM; Grilli and Subramanya, 1996; Grilli and Horillo, 1997), was extended and used to simulate the shoaling of incident periodic waves, including dynamic effects due to their local interaction with the bottom or an obstacle/mine, up to near breaking and subsequent dissipation in an absorbing beach (see sketch in Fig. 1). Such simulations were extensively validated by comparison with laboratory experiments (Grilli et al., 1994, 1997a,b, 2004), which confirmed that FNPF theory is very accurate to model gravity wave transformation over complex bottom topography, up to and including wave overturning.

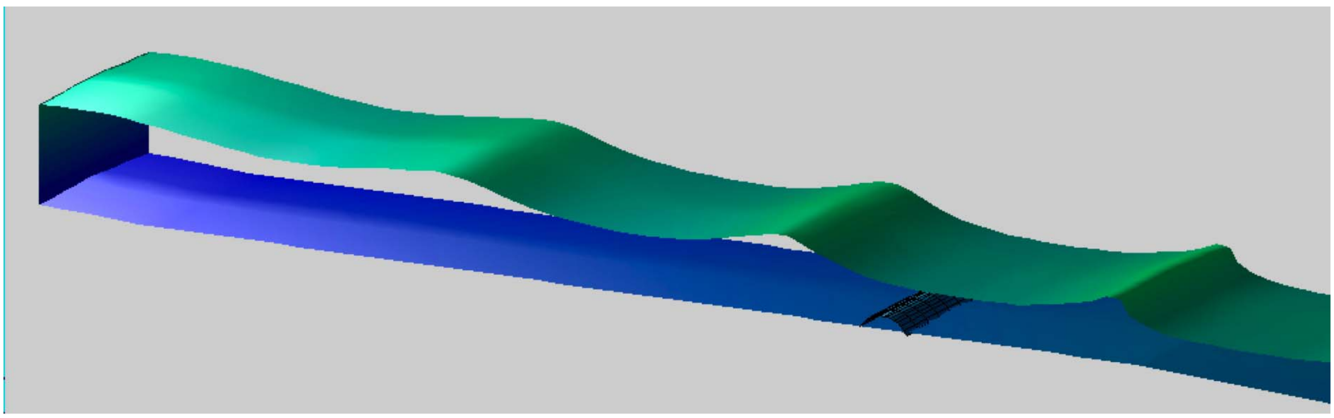

Figure 1: Sketch of 2D-NWT, with piston wavemaker on the left-hand side, a sloping bottom, with a cylindrical, partially buried object, and an absorbing beach on the right hand side, where waves break.

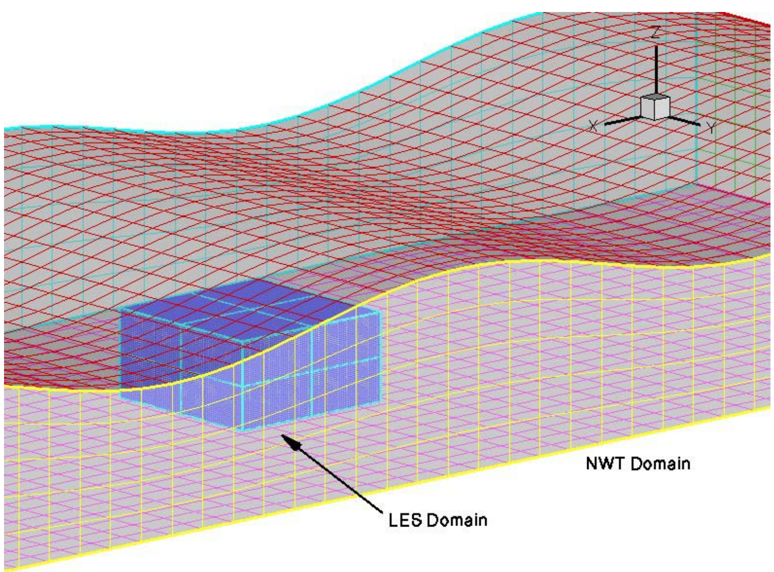

Figure 2: Sketch of the NWT domain with embedded 3D NS-LES domain Ω_{LES}

The hydrodynamic forcing from incident waves is calculated in the 2D-NWT, over a small near-bottom 3D region Ω_{LES} containing the moving sediment covered seabed and the buried object, in which 3D-NS-LES and sediment transport computations are performed (Fig. 2). Assuming long-crested incident swells, wave forcing is expressed in terms of 2D velocity and pressure fields. In the earlier phase, computations in the 2D-NWT were made for a wide range of parameters (incident wave height and period, obstacle size and percentage of burial, and sandy bottom). Wave elevation and particle velocities near the obstacles were compared to laboratory experiments, performed at Arizona State University (Voropayev et al., 2003), thus providing a physical validation of the simulated forcing wave fields (Grilli et al., 2003, 2006). In the past year, we have implemented and tested the generation of more realistic *fully nonlinear irregular waves* with specified energy spectrum (see Results section).

The NS-LES computations performed in Ω_{LES} are fully 3D, which is essential for large-eddy simulations and sediment transport calculations. These computations are both initialized and forced in real time by wave-induced hydrodynamic fields. In the first year, only periodic swells were used and forcing for one period of NWT computations was repeated in a loop in the NS-LES model. In the past year, the model coupling was extended to apply to *long time series of arbitrary wave forcing* (see Results section). In the earlier phase, drawing on past experience in simulating oscillatory flows (Zedler and Street, 2001), after experimenting with several schemes, the 3D-NS-LES model was driven by specifying the *wave-induced pressure gradients* from the NWT model as *source terms* into the NS-LES momentum equations (Gilbert et al., 2005, 2007). In the past year, a *new formulation* of model coupling has been implemented, based on a *perturbation flow approach*, which was shown to be both more consistent and accurate (see Results section).

Because of the BEM solution, only the 2D-NWT boundary is discretized; the smaller Ω_{LES} region (Fig. 2), however, has a 3D finite difference numerical grid, highly-resolved in the vertical plane and less so in the direction normal to the main flow direction, to fully capture all the details of turbulent motion, particularly near the seabed, and accurately compute velocity, pressure, and Suspended Sediment Concentrations (SSC) (see, Zang et al., 1993, 1994; Zedler and Street, 2001, 2002, for background of the 3D-NS-LES model).

Rationale for this work : The near-bottom wave-induced flow that forces sediment transport can be simulated using a standard 3D-NS-LES model, for arbitrary bottom topography with/without obstacles, at a few meter scale. This, however, requires computing at a larger scale (hundreds of meters) the background flow induced by nonlinear shoaling waves (and possibly currents), including effects induced by the bottom and obstacle/mine, from the far-field to the location of Ω_{LES}. The 2D-NWT provides a very efficient and accurate solution to the larger scale problem and the full coupling NWT-LNS-LES, particularly using the most recent perturbation flow method, provides a seamless transition of computations from one model to another. The approach is also amenable to parallel computations.

Key individuals at URI : In the past fiscal year, the PI has worked on the project with two graduate students. Nate Greene, a new graduate student, joined the project in the Summer 2006 and has since concentrated on performing nonlinear irregular waves simulations in the NWT. Additionally, since the Spring 2006, Jeff Harris, a Ph.D student who has been awarded a 3-year NDSEG fellowship, has worked full time on all computational aspects of the project related to the 3D-NS-LES model, at no cost to ONR.

WORK COMPLETED

In this two-year project, with the goal to perform more general and physically meaningful simulations of wave-induced sediment transport for seabed-obstacle evolution, we have pursued the development, testing and validation of the coupled NWT-NS-LES model along the following directions :

(1) During the first year of the project, we had implemented and run the same 2D-NWT and 3D-NS-LES models as developed in the previous phase, on URI's 8-node computer cluster. In the past year the model structure was modified in-depth by: (i) implementing a new *perturbation flow approach* for the NS-LES computations (further discussed in this report); (ii) and performing additional *parallelizations and optimizations* of both model codes.

(2) *Extension work* initiated during the first year was continued in the past year, for the NS-LES and embedded sediment transport models, including implementing : (i) a sloping bottom; (ii) a more realistic and physically meaningful sediment pick-up algorithm (i.e., specifying the gradient of the SSC using a pickup function, instead of specifying the SSC at some point above the seabed); (iii) a logarithmic-layer near the bottom, rather than using a no-slip boundary condition (which is less accurate unless the viscous sublayer can be resolved); and (iv) forcing the model by arbitrary irregular, fully nonlinear, incident wave fields. For the latter extension (iv), limited simulations in the NWT had been made, but we now are able to generate fully nonlinear incident wave fields, corresponding to a specified energy spectrum (e.g., JONSWAP) (see Results section).

(3) In the first year, the NS-LES code flowchart and structure had been modified to make them general in geometry and parameters, based on user-specified data (in the previous phase, the models were "hard-wired" to only solve one problem). In the past year, we run new applications aimed at *testing and validating the various aspects of the model* (see Results section in this report). More work is still required, however, to make the coupled model fully general in both incident wave fields and geometry of the obstacle and ocean bottom.

(4) During the latter part of the past year, we were granted access to, and resources on one of the DoD *massively parallel supercomputer clusters* (with over 2000 processors). We have then been experimenting with both compiling and running the generalized and parallelized NWT and NS-LES models on this powerful computer. Once the coupled model is fully operational on this large cluster, we will run *sensitivity analysis* (i.e., convergence and accuracy) studies of model results to grid size and numerical parameter values.

(5) During their initial development in the previous phase of this project, both models were run in sequence, which required a number of manual steps (some of these involving using small MATLAB programs). In the past year, we have achieve the *fully automated coupling and running* of both models on the clusters.

RESULTS

Wave generation : In the past year, we extended the 2D-NWT to simlate fully nonlinear irregular shoaling incident wave fields, with deep water wave input based on standard energy spectra (e.g., JONSWAP, PM). Figure 3, for instance shows a 2D simulated free surface corresponding to a typical

New England shelf average seastate (H_s=1.2 m, T_p=5 s, depth 50 m). We are experimenting with two methods for performing such nonlinear irregular wave simulations in the NWT, with the coupled model, which are still being tested. In the first method, illustrated in Fig. 3, we : (i) initialize simulations by first creating a linear sea-state based on a specified spectrum, over constant depth, using the standard random phase method; (ii) use the efficient Higher Order Spectral (HOS) method (Dommermuth and Yue, 1987), with ramp-up procedure (Dommermuth, 2000), to evolve the linear sea-state towards full nonlinearity; and (iii) once reaching fully nonlinear quasi-permanent conditions in the HOS model over constant depth, waves are finally specified as input condition into the 2D-FNPF for further simulations. In the second method, illustrated in Fig. 4, we generate irregular waves in the NWT using a wavemaker, starting from still water conditions (e.g., Fig. 1). The wavemaker stroke spectrum is obtained from the wave energy spectrum, using the usual linear superposition and transfer function. After generating waves, as in a physical wavetank, the wavemaker law of motion is iteratively corrected to achieve the target spectrum in the NWT. Although the second method is more computationally intensive, it allows for an arbitrary geometry of the NWT boundary, while the HOS-based method is limited to constant water depth. In Fig. 4, irregular waves are generated for a wind wave spectrum with H_s= 0.6 m, T_p= 2.2 s, in depth d = 6.4 m. We see a sequence of free surfaces generated in the NWT, with a ramp-up from Fig. 4a-d, to reach almost a steady state in Fig. 4e, where incident irregular waves are absorbed in the absorbing beach (for x'> 4.5). The dominant wave height is around 0.1d, as expected and the dominant wavelength is about 0.5d = 3.2 m.

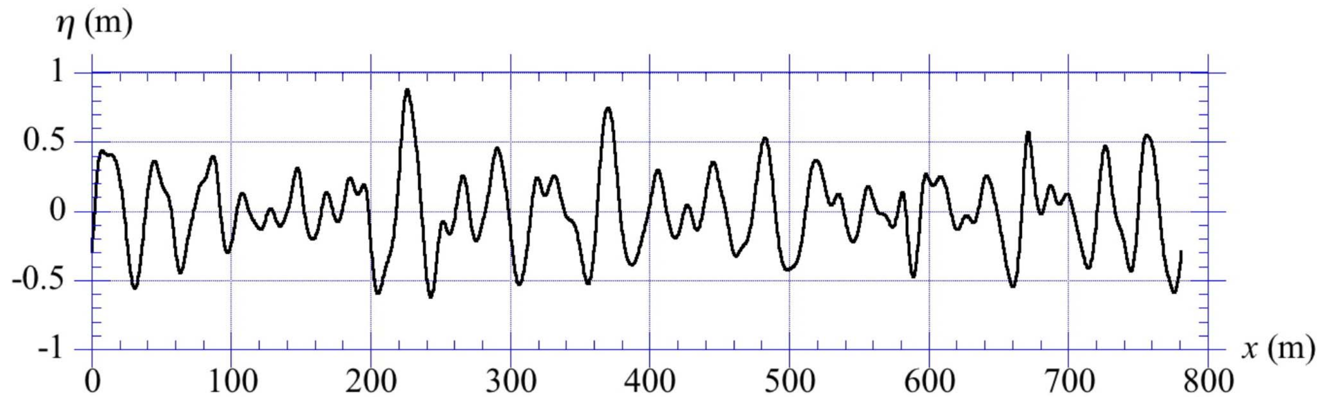

Figure 3: Sketch of fully nonlinear irregular waves computed with the HOS method, as input condition for the 2D-FNPF-NWT model, based on a JONSWAP spectrum (H_s=1.2 m, T_p=5 s, depth = 50 m).

New `perturbation flow' coupling method : In this method, which we implemented in the past year, the total velocity and pressure fields ($\mathbf{u}$, p) are divided into the sum of an inviscid wave part ($\mathbf{u}_w$, p_w) and a viscous perturbation part ($\mathbf{u}_v$, p_v). The inviscid, irrotational, wave fields are known from the NWT solution, and can directly be computed in the BEM model for any time step, throughout the 3D-NS-LES domain Ω_{LES}. NS-LES equations and boundary conditions are then rewritten in terms of the perturbation fields, while treating the wave fields as known forcing terms, at a given time step. The (linear) mass conservation equation keeps the same form as before for the perturbation velocity (since the wave velocity already satisfies continuity equation in the NWT), and is solved as a Poisson equation in the model. Because of nonlinear convective terms in the momentum equations, interaction

terms between wave and perturbation fields must be calculated in realtime. One advantage of the new formulation is, perturbation fields now naturally decay in the model, away from the seabed and obstacle, and naturally satisfy a radiation condition on the outer boundary of domain Ω_{LES}. This was not the case in the earlier implementation (e.g., Gilbert et al., 2007). Details of this formulation will be reported in Harris and Grilli (2007) and Grilli, Harris and Greene (2007). Note, this new implementation, with a flow decomposition, is exact in the equations and hence does not require any new approximation, except as before that the perturbation from the NS-LES flow on the NWT solution is neglected, which is relevant considering the scales of the wave and sediment transport flows.

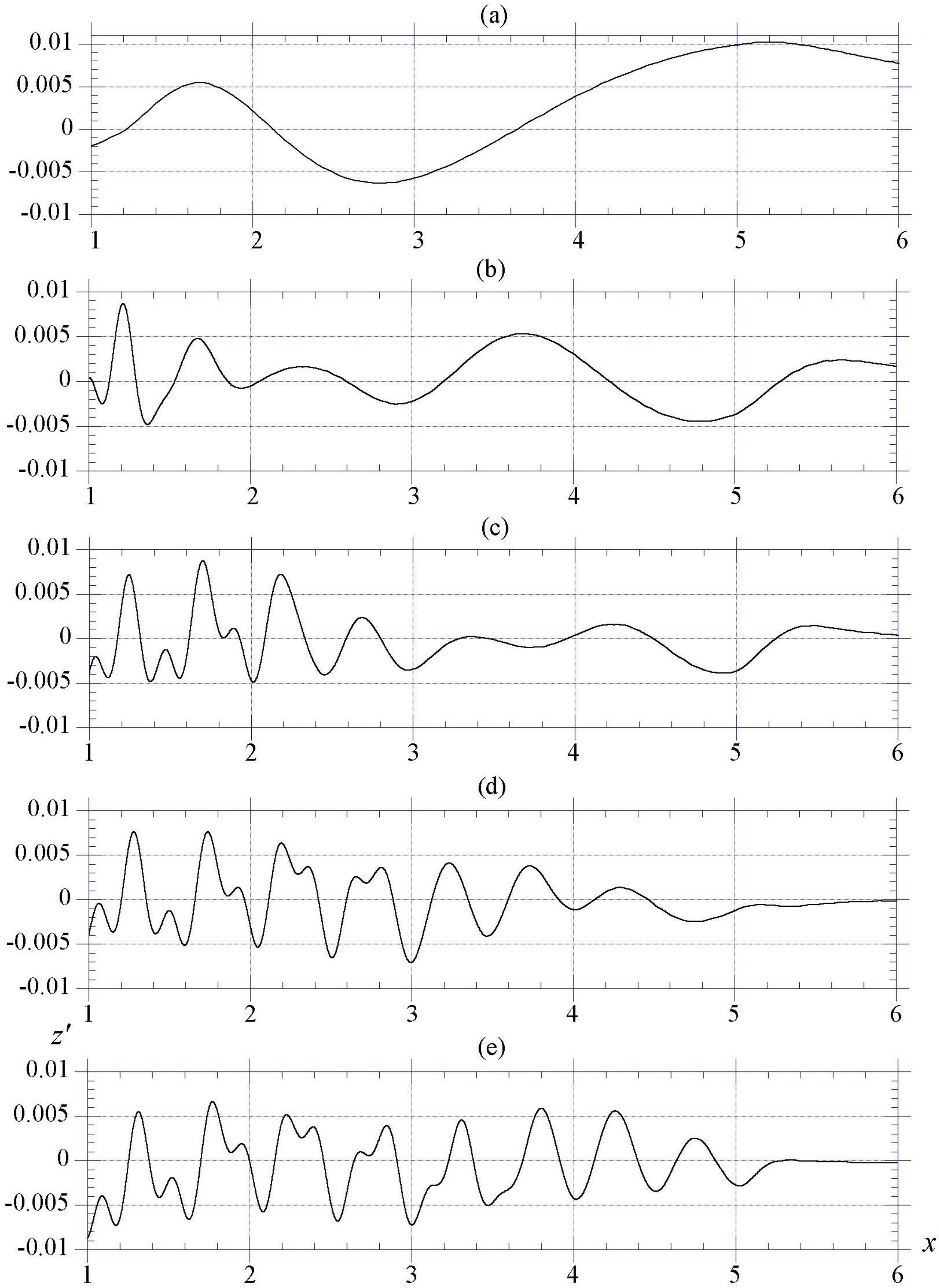

Figure 4: Sketch of fully nonlinear irregular waves directly generated with a wavemaker (at x' = 0) in the 2D-FNPF-NWT model, based on a JONSWAP spectrum (H_s= 0.6 m, T_p= 2.2 s, d = 6.4 m), with t/T = (a) 5, (b) 9, (c) 13, (d) 17, (e) 21, T/Δt = 100, and the absorbing beach starts at x' = 4.5. We define x' = x/d and z'=z/d.

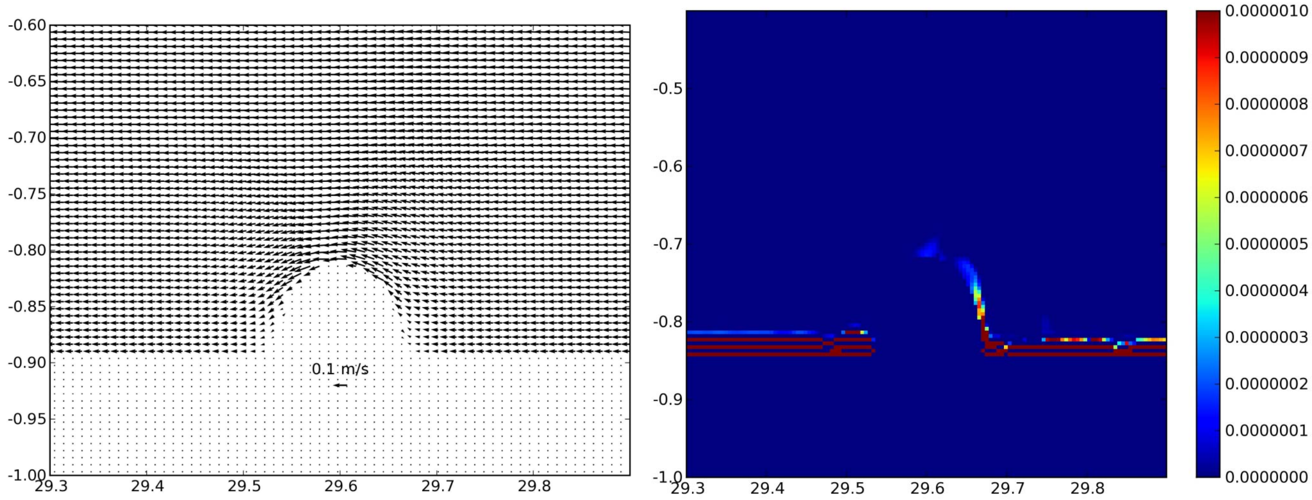

Figure 5 : wave-induced periodic flow (3 s period) around a 75% buried cylinder in a flat sandy bottom (with d_{50} = 200μm). (a) Velocity vectors; and (b) sediment concentration. Axes are in meter.

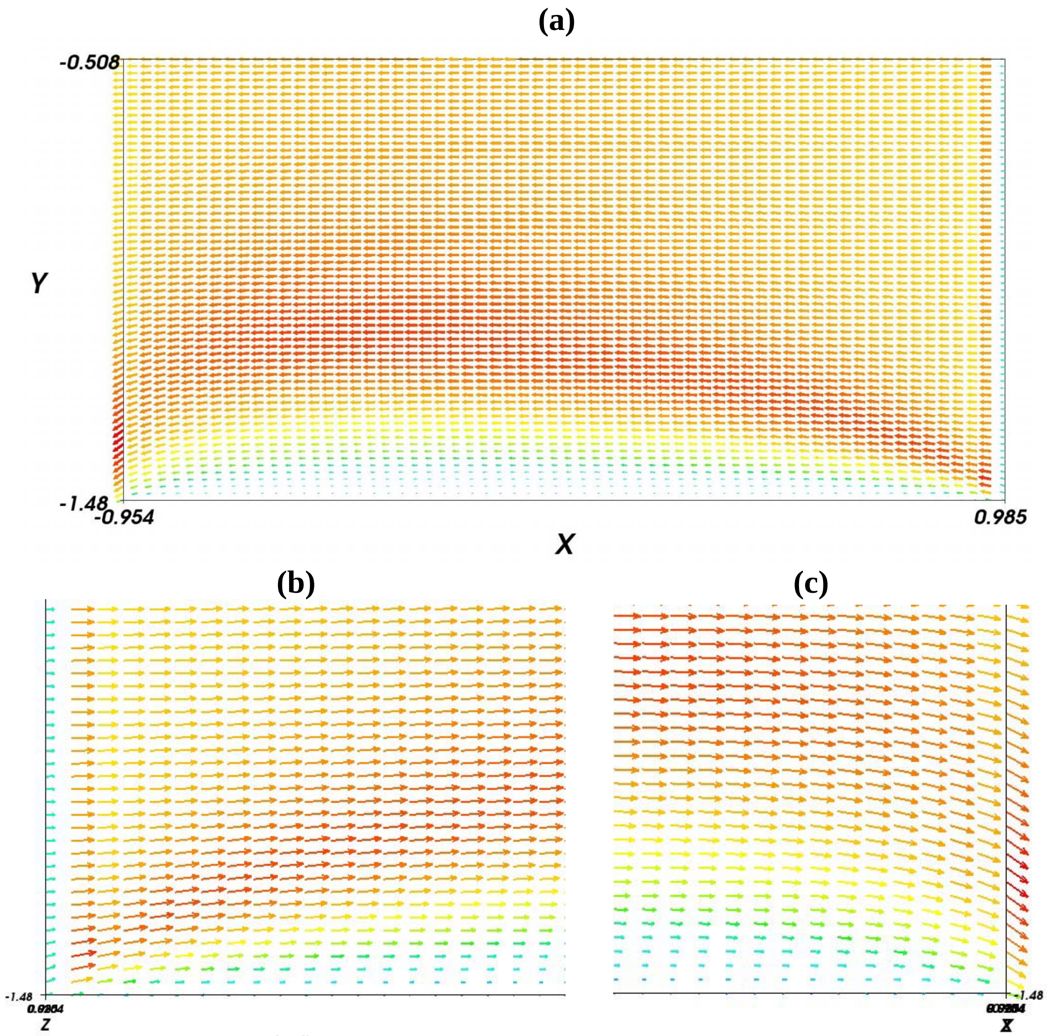

Figure 6: Examples of theoretical flow computations for verification using the NS-LES model. (a) Blasius flow (middle section); (b) leading edge flow; (c) trailing edge flow.

Flow and sediment transport simulations : In its current more general (i.e., using the perturbation flow) and parallelized version (see section on Work completed), the coupled NWT-NS-LES model can perform realistic and physically meaningful simulations of wave-induced sediment transport over a partially buried obstacle located on a sloping bottom covered with sediment.

Last year's report showed an *example* of coupled NWT-NS-LES hydrodynamic model simulations for a purely periodic wave forcing. In the past year, we verified that *these results could be retrieved* using the more recent model implementation, with the new coupling method (flow perturbation) and parallel model implementation on the clusters. Figure 5 shows an example of such verification computations for a wave-induced periodic flow around a 75% buried cylinder, in a flat sandy bottom (with d_{50} = 200 μm), at some time during one wave period. Velocity vectors are shown in Fig. 5a and sediment concentration is shown at the same time in Fig. 5b. The forcing flow is a 3 s period wave, with maximum horizontal current velocity of 0.05 m/s. The arbitrary sediment pickup law is still used in

this computation, whereby the SSC is specified at the nearest point above the seabed dependent on the friction velocity (see, Gilbert et al., 2007).

To better validate the various aspects of the NS-LES model, in relation to *numerical parameter values*, particularly regarding the flow induced in the *bottom boundary layer,* in the past year, the model was run for standard or academic type flows, whose solution is either known from analytical solutions, experiments, or other numerical solutions. Figure 6 shows examples of such *validation applications,* for a Blasius flow (a) (i.e., viscous flow near the middle of a long, theoretically infinite, plate, and flows at the leading (b) and trailing (c) edge of such a plate). The figure shows that computed flows, materialized by velocity vectors, follow the expected pattern in the boundary layer near the plate.

Other applications are curretnly being run to test the new sediment and moving bed algorithms; the model is thus expected to predict bed evolution, near and around a bottom obstacle, as a function of time (i.e., burial/scouring) for periodic or irregular wave forcing. Such results will be reported in the forthcoming papers (Harris and Grilli, 2007; and Grilli, Harris and Greene, 2007)

IMPACT/APPLICATIONS

We are developing an efficient and accurate numerical simulation tool for large-scale far field wave forcing in a 2D-NWT model, and detailed representation of induced near-bed flows and sediment transport, by large-eddy simulation, in a near field 3D-NS-LES model. This tool has great potential for both improving our fundamental understanding of wave-induced sediment transport processes and predicting the burial and unburial of objects, partally buried on the coastal ocean bed, and for predicting ripple and dune formation and evolution (e.g., Voropayev et al., 1999).

In a larger context, this work will yield an experimentally-validated numerical tool for studying nearshore wave climates and induced sediment transport and geomorphodynamic bottom changes. The efficiency and versatility of the proposed coupled model will allow, in future work, investigating new classes of problems of interest to various ONR programs. Specifically, the present problematic and methodology directly relate to the objectives of the ONR Wave/Mud Interaction MURI and Tidal Flats DRI projects. In particular, the model should ultimately help in assessing and simulating the effects of dissipation, due to sandy or muddy bottom sediment and morphodynamic changes induced on the bottom by the combined effects of waves and tidal currents, on nearshore wave transformations and wave parameters observable through remote sensing (e.g., wave steepness, wavelength, surface slope and curvature).

REFERENCES

Dommermuth, D.G. and Yue, D.K.P. (1987) “A High Order Spectral Method for the Study of Nonlinear Gravity Waves. ” *J. Fluid Mech*., **184**, 267-288.

Dommermuth, D.G. (2000) “The initialization of nonlinear waves using an adjustment scheme”. *Wave Motion*, **32**, 307–317.

Gilbert, R.W. (2005) *Numerical modeling and validation of nonlinear wave driven sediment transport*. M.S. Thesis, Department of Ocean Engineering, University of Rhode Island, 132 pps.

Gilbert R.W., Zedler E.A., Grilli S.T. and Street R.L. (2005) “Modelling of Wave-Driven Sediment Transport in the Shoaling Zone.” In *Proc. 5th Intl. Symp. on Ocean Wave Measurement and Analysis* (WAVES 2005, Madrid, Spain, July 2005), IAHR Publication, paper 121, 10 pps.

Grilli, S.T., Gilbert, R.W., Lubin, P., Vincent, S., Legendre, D., Duvam, M., Kimmoun, O., Branger, H., Devrard, D., Fraunie, P., Abadie, S. (2004) "Numerical modeling and experiments for solitary wave shoaling and breaking over a sloping beach." In *Proc. 14th Offshore and Polar Engng. Conf.* (ISOPE04, Toulon, France, May 2004), 306-312.
Grilli, S.T. and J. Horrillo (1997). "Numerical generation and absorption of fully nonlinear periodic waves*." J. Engng. Mech.*, **123**(10), 1060-1069.
Grilli, S.T., Subramanya, R., Svendsen, I.A. and J., Veeramony (1994) "Shoaling of solitary waves on plane beaches," *J. Waterway Port Coastal and Ocean Engng.*, **120**(6), 609-628.
Grilli, S.T. and Subramanya, R. (1996) "Numerical Modeling of Wave Breaking Induced by Fixed or Moving Boundaries." *Computational Mechanics*, **17**(6), 374-391.
Grilli, S.T., Svendsen, I.A. and R., Subramanya (1997a) "Breaking criterion and characteristics for solitary waves on slopes," *J. Waterway Port Coastal and Ocean Engng.*, **123**(3), 102-112.
Grilli, S.T., Svendsen, I.A. and R., Subramanya (1997b) Closure of :"Breaking criterion and characteristics for solitary waves on slopes*," J. Waterway Port Coastal and Ocean Engng.*, **124**(6), 333-335.
Grilli, S.T., Voropayev, S., Testik, F.Y. and H.J.S., Fernando (2003) "Numerical Modeling and Experiments of Wave Shoaling over Buried Cylinders in Sandy Bottom." In *Proc. 13th Offshore and Polar Engng. Conf.* (ISOPE03, Honolulu, USA, May 2003), 405-412.
Grilli, S.T., Voropayev, S., Testik, F.Y. and H.J.S., Fernando (2006) "Numerical modeling and experiments of periodic waves shoaling over semi-buried cylinders in sandy bottom." *J. Waterway Port Coastal and Ocean Engng.* (in revision).
Voropayev, S.I., McEachern, G.B., Boyer, D.L. and Fernando, H.J.S. (1999). "Dynamics of sand ripples and burial/scouring of cobbles in oscillatory flow." *Applied Ocean Res.*, **21**(5), 249-261.
Voropayev, S. I., Testik, F. Y., Fernando, H. J. S., and D. L. , Boyer (2003) "Burial and scour around short cylinder under progressive shoaling waves." *Ocean Engng.*, **30**(13), 1647–1667.
Zang, Y., Street, R. L., and J. R., Koseff (1993) "A dynamic mixed subgrid-scale model and its application to turbulent recirculating-flows." *Phys. Fluids A: Fluid Dynamics*, **5**(12), 3186–3196.
Zang, Y., Street, R. L., and J. R., Koseff, (1994) "A non-staggered grid, fractional step method for time dependent incompressible Navier-Stokes equations in curvilinear coordinates." *J. Computational Phys.*, **114**(1), 18–33.
Zedler, E.A. and Street, R.L. (2001) "Large Eddy Simulation of sediment transport: Currents over ripples." *Journal of Hydraulic Engineering*, **127**(6), pp. 444-452.
Zedler, E.A. and Street, R.L. (2002) "Nearshore sediment transport processes: unearthed by Large Eddy Simulation." In *Proc. 28th International Conference on Coastal Engineering*, ASCE, pp. 2504-2516.

PUBLICATIONS

Gilbert R.W., Zedler E.A., Grilli S.T., and Street R.L. (2007) "Progress on Nonlinear-Wave-Forced Sediment Transport Simulation." *IEEE Journal of Oceanic Engineering*, **32**(1), 236-248, doi:10.1109/JOE.2007.890979.

Grilli, S.T., Harris, J. and Greene, N. (2007) "Modeling of Wave-induced Sediment Transport in the Shoaling Zone in the Presence of Bottom Obstacles". Submitted to *Intl. Coastal Engineering Conference* (ICCE 2008, Hamburg, Germany).

Harris, J. and Grilli, S.T. (2007) "Validating a perturbation approach to the large eddy simulation of wave-induced sediment transport". Abstract submitted to *AGU Fall Meeting* (San Francisco, USA, 12/07).